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Fiber Optic Strain Sensors (FOSS) to Monitor Strains on a Navy Vessel During Operations

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14. ABSTRACT

This document summarizes the recent deployment of a fiber optic strain sensing (FOSS) system to monitor loads on a Navy Vessel, as requested and authorized by Commander Naval Surface Force, Atlantic. The objectives were to 1) conduct an in-service validation of the technology onboard a U.S. Navy ship and 2) determine contributing influences to recurring cracking of [new] deckplate, as described by the Southeast Regional Maintenance Center (SERMC) Port Engineer. Previous NAVSEA investigations discuss sensitization of the aluminum and onset of stress corrosion cracking (SCC), although the source of the SCC stresses have never been characterized. This effort attempts to quantify performance of the FOSS technology as a tool to provide such characterization. Covered in this document are the instrumentation, data collection, and subsequent analysis.

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Executive Summary:

This document summarizes the recent deployment of a fiber optic strain sensing (FOSS) system to monitor loads on a Navy Vessel, as requested and authorized by Commander Naval Surface Force, Atlantic. The objectives were to 1) conduct an in-service validation of the technology onboard a U.S. Navy ship and 2) determine contributing influences to recurring cracking of [new] deckplate, as described by the Southeast Regional Maintenance Center (SERMC) Port Engineer. Previous NAVSEA investigations discuss sensitization of the aluminum and onset of stress corrosion cracking (SCC), although the source of the SCC stresses have never been characterized. This effort attempts to quantify performance of the FOSS technology as a tool to provide such characterization. Covered in this document are the instrumentation, data collection, and subsequent analysis.

These initial FOSS test results *indicate that large compressive and shear stresses develop in the deckplate during transit and correlate to engine load. These stresses are either the primary cause of or a major contributing factor* to the [replaced] deckplate cracking. Results also indicate that ship maneuvering, ambient vibrations, thermal expansion, and slewing of the AN/SPG-62 Illuminator exert negligible influence in stressing the deckplate.

Introduction

A number of the CG class vessels in the U. S. Navy are experiencing cracking at various locations on the aluminum superstructure. The cracking has been observed on the 04 level deckplate, the overhead of one of the AN/SPG-62 Illuminator rooms, the intake bulkhead, and several other locations on the deckplate of one particular class of vessel[i,ii]. The cracking is, in many cases, persistent, recurrent (even after repairs), and has the potential to influence mission critical operations aboard ships.

Currently, the cause of this cracking has been investigated and is believed to be due to stress corrosion caused by sensitization of the aluminum alloy used in construction (5456 material). However, in order for this type of cracking to initiate and persist the material must be sustaining large stresses. It is the origin of these stresses that is still in question. The goal of this work was to instrument one of the affected areas, monitor the stresses over a 36 hour period during transit, and try to discern the types of ship maneuvers, or ambient conditions that are leading to stress concentrations. The specific area under observation was the deckplate [overhead] of the #4 Radar room (05-316-0-C) onboard a ship from the affected class. This location was chosen due to the fact that there has been repeated cracking of this deckplate and because this room provided the most convenient, unobstructed location for installation.

The sensing system used for this application was a fiber optic strain sensing system developed at the Naval Research Laboratory (NRL). This system is ideal for use in monitoring stresses in corrosive environments (in this case a marine environment), is lightweight and unintrusive, and is capable of measuring slowly varying stresses (down to DC) with high accuracy. The rest of this report is organized as follows (with hyperlinks):

Section 1 describes the installation of the FOSS system

Section 2 describes the data collection process, including a description of the test matrix used to discern the cause of the stresses

Section 3 shows some of the analysis of the resulting data

Section 4 concludes with an assessment of the most likely cause of the large stresses experienced by the deckplate. Recommendations for future monitoring work are also discussed.

Section 5 provides a future vision of how enabling or empowering this technology can be.

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Section 1: Installation

Installation of the sensing system was performed during a single day, 15 May 2007. Four fiber Bragg grating (FBG) rosettes were installed in the overhead of #4 Radar (05-316-0-C) where the ship had previously experienced cracking. This space houses mission critical equipment (both communications and weapons) and was therefore deemed an ideal candidate for monitoring. Additionally, this particular location allowed for the simplest, most un-intrusive installation of all potential areas surveyed. Figure (1) shows the radar room from both the outside and inside.

Figure 1: (left) Outside view of #4 radar room showing rough location of the installation. This room houses both communications and weapons equipment. (right) Inside #4 radar room. Communications equipment located directly below location where cracks have been observed.

A total of 17 FBGs were installed in order to monitor the deck strains. Four FBG strain "rosettes", each consisting of 3 FBG sensors, were used to monitor the principle strains.

Figure (2) shows one of the FBG rosettes. In order to access the deckplate the foam insulation was removed, the paint was sanded away, and acetone wipes were used to provide a proper surface preparation for mounting. Once the gratings were installed, the insulation was replaced. The only visible sign that the sensing system was installed were two fibers protruding from the overhead.

Figure 2: One of the FBG rosettes installed on the deckplate below the foam insulation. Insulation was removed with a knife, the deckplate was sanded down to create a bare aluminum surface. Each FBG rosettes consists of 3 gratings measuring strains at 0, 45, and 90 degrees relative to the longitudinal axis of the ship (0^0).

An additional single Bragg grating was installed and left un-attached to the deckplate. This sensor was used as a temperature sensor. Because this sensor is uncoupled from the deckplate, any observed strain will be due to temperature effects. Finally, a set of four temperature compensated gratings were installed external to the deckplate. These sensors were a-thermal FBGs, which were used to calibrate the sensing system in real-time such that any thermal drift in the hardware was automatically corrected.

The computer and hardware used to monitor the strains were placed on a small wooden shelf near the back corner of the room. This area does not house any mission critical equipment and the shelf was unoccupied. Figure (3) shows both the final locations of the strain rosettes (once the foam was replaced) along with a picture of the sensing equipment used to record the strain data. The rosettes will be referred to as A, B, C, and D in this document.

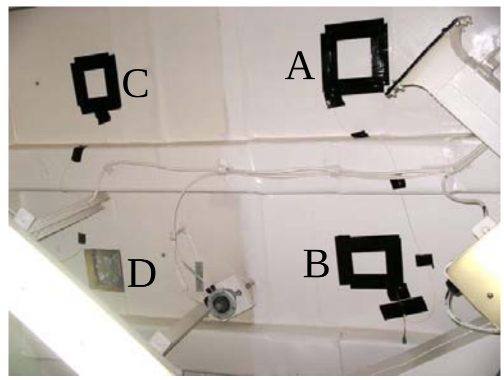

Figure 3: Computer and demodulation hardware located on middle shelf (left). The overhead directly above these shelves is where the gratings were located. The four FBG rosettes (A,B,C,D) with most of the insulation replaced (right).

Section 2: Data Collection

The goal of this study was to monitor the strains on this deckplate over a period of two days. Most of the phenomena we were hoping to capture were low frequency motions. For this reason the sampling rate used in acquiring the data was set to 360Hz. During transit the ship performed several maneuvers in order to help us determine the cause of the large strains. Two different potential loading mechanisms were explored. First a series of tests were coordinated with the ships' Captain whereby the ship performed "hard turns" at a variety of increasing speeds. The goal here was to discern the effects of inertial loading on the deckplate resulting from simulated combat maneuvers.

Next, the AN/SPG-62 Illuminator was rotated to determine its influence on the deck strains. The maximum rotational speed this particular AN/SPG-62 Illuminator can achieve is roughly 1/6 Hz. (thus the sampling rate is more than sufficient).

During the acquisition, data were written to file approximately every 10 minutes. This was to ensure most of the acquired data would not be destroyed in the event of a system failure. All data files were time-stamped so that they could later be correlated with the previously mentioned ship maneuvers.

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Section 3: Results and Analysis

During the trip, the FBG demodulation system was restarted thrice as a way to insure the validity of at least one portion of the data. Upon each restart, the system automatically sets all strains to zero. In evaluating the data, it was clear that there were no fundamental problems with the hardware. This meant that the data set following a restart could be spliced onto the previous data simply by adding the final strain measurement in the previous data to the initial zero of the new data and adding a time offset. While this may introduce an error of a few microstrain, since the measured strains were millistrains the error is negligible. The strains recorded by each leg of a rosette were converted to principle strains and a strain angle using the expressions

$$\varepsilon_{1,2} = \frac{\varepsilon_0 + \varepsilon_{90}}{2} \pm \sqrt{\left(\frac{\varepsilon_0 - \varepsilon_{90}}{2}\right)^2 + \left(\frac{2\varepsilon_{45} - \varepsilon_0 + \varepsilon_{90}}{2}\right)^2}$$

$$\theta = \frac{1}{2}\tan^{-1}\left(\frac{2\varepsilon_{45} - \varepsilon_0 + \varepsilon_{90}}{(\varepsilon_0 - \varepsilon_{90})}\right)$$

The principle strains result from projecting the strain field onto directions of maximum and minimum normal strains only (no shear). The angle associated with this projection is the strain angle, θ. This angle provides the directions along which the maximum (and minimum) strains are acting. All strains were converted to stresses by assuming linear elastic behavior with an elastic modulus of 10,000ksi for the deck material (5456 H117 Aluminum).

Figure 4 shows plots of the principle stresses versus time for rosettes C and D (see again Fig. 3 for rosette placement). A software glitch invalidated the results from rosettes A and B as well as the thermal compensation sensor. Thus the results shown in Fig. 4 do not have thermal effects in the optical fiber removed. In this figure note that the measured stresses are all compressive, with the largest magnitudes beginning about 2000 hours and ending near 0600 the next morning. Also plotted is a measure of engine load (shaft rpm x pitch). During transit we noticed that the observed strains seemed to correlate somewhat with speed. Indeed, the data shows a strong correlation between engine load and deckplate compressive stress. As the ship picks up speed, the stress observed in the deckplate tends to increase. This may be due to thermal loading from the engine transferring to and stabilizing in the ship structure or perhaps direct structural loading resulting from drag created by speed increases. Regardless, a phenomena showing strong correlation to engine load appears to be at least one of the primary mechanisms causing excessive stress in the deckplate. Also plotted in Fig. 4 is the yield stress for the deckplate material.

COMMENT OF INTEREST

Based on the data, it appears the deckplate stress is roughly ½ the yield stress (32ksi).

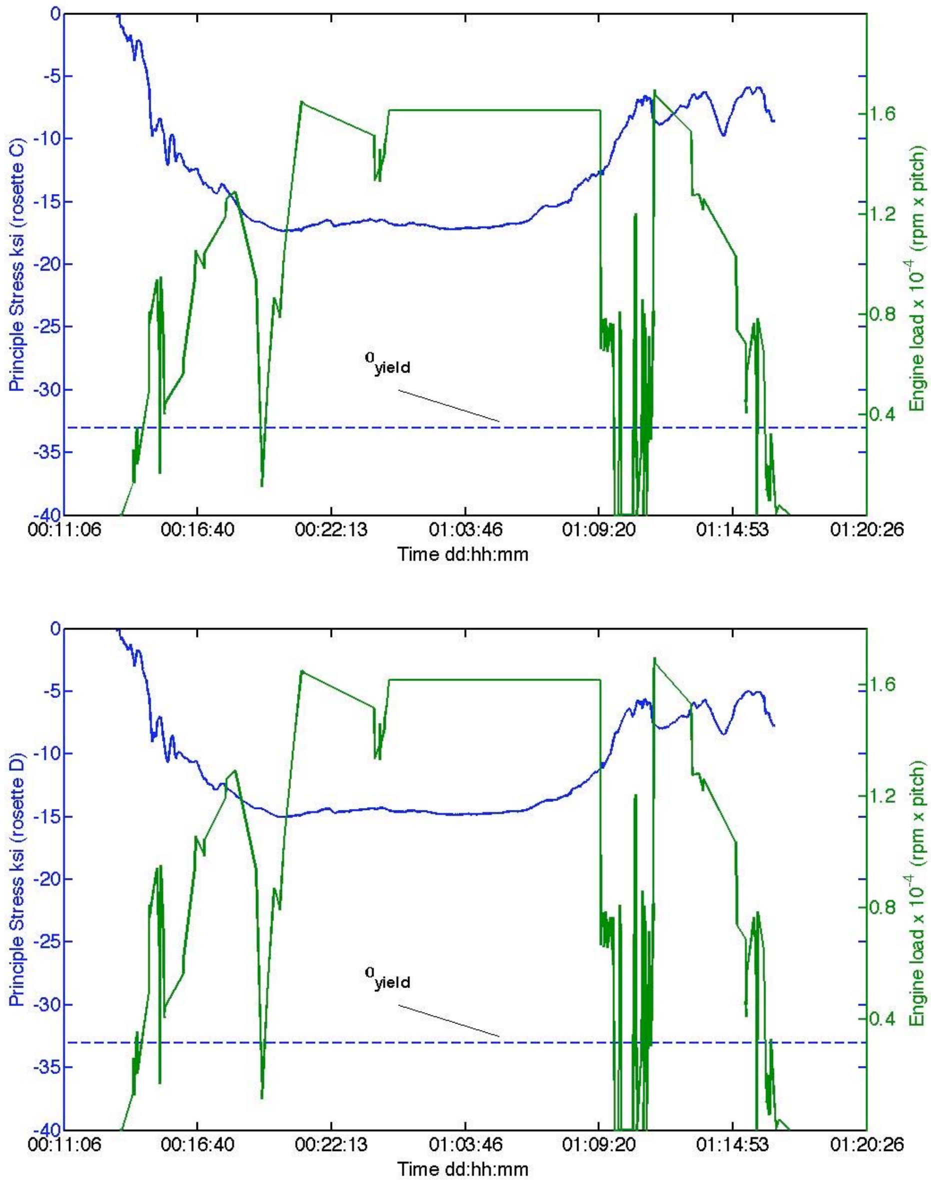

Figure 4. Principle stresses recorded during the trip from rosettes C & D. Also shown is the yield stress for the deck material. Note that the largest stresses began near sunset on 6/7/07 and ended about sunrise on 6/8/07. Stress correlates well with engine load.

There is also the possibility that the observed stresses are influenced by air temperature or solar heating of the deckplate. However, an estimation of potential temperature changes shows that while such effects may modify our results, they are not the primary source of the observed stress. Our estimation assumes that the overnight deck temperature drops to 70 °F (21 °C) with a maximum deck temperature at mid-afternoon of 140 °F (60 °C) and a worst-case wavelength shift of the fiber in response to temperature changes of 12.6 $\mu\varepsilon$/°C. This would result in an apparent strain of + 490 $\mu\varepsilon$ (4.9 ksi stress). Such a temperature shift would further exacerbate the indicated compressive strains displayed in Fig. 4.

It's also worth noting that the maximum principle stresses are similar for both rosettes while the minimum strains differ significantly. This indicates that the mean strain is varying across the plate. It's also important to understand that there is no way of knowing what residual stresses existed in the deckplate at the time that our measurements were started. Thus, the deckplate may have initially been in tension and could have possibly remained in tension for the trip duration (depending on how large the initial tension was). It is also possible that the deckplate could have experienced some combination of initial tension changing to compression and back. Nevertheless, the variations in strain magnitude, up to 50% yield of the base metal, indicate a [predicted] cyclic phenomenon that appears to correlate to engine load.

Figure (5) shows a plot of the strain angles corresponding to rosettes C and D. For much of the trip the strain angles were roughly +/- 20^o. The resulting directions of maximal strain are such that a large amount of shear may be occurring on the plate (see right plot of Fig. (5)).

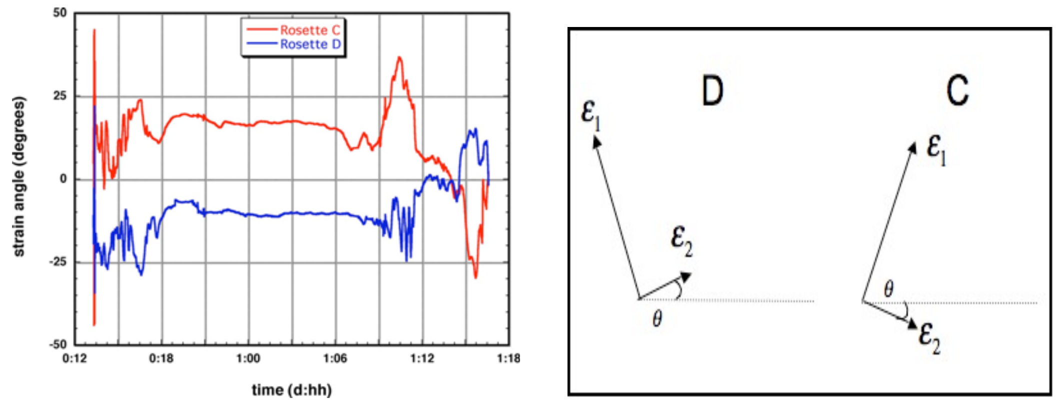

Figure 5. Principle strain angles measured during the trip by rosettes C (red) and D (blue). The right plot is a rough illustration of the principle strain directions as measured from sunset on 6/7/07 to sunrise on 6/8/07

In order to determine the influence of ship maneuvers on the deck strains a series of turns were performed at varying speeds. Beginning at approximately 19:24 the ships speed was reduced to 8 knots. The speed was then slowly increased over the course of the next 45 minutes to 20 knots. At 20:11, moving at 20 knots, the ship performed a sharp right turn ("hard rudder right"), followed by a hard left turn, followed by another hard right turn. The entire sequence lasted approximately 5 minutes. The ships speed was then increased to 27 knots and the same sequence of turns was conducted. Finally, the ship speed was set in excess of 27 knots and the sequence repeated once more. This final set of turns was completed at 21:00.

Time (min.)	Speed (knots)
9	14
15	20
35	20
40	28.5
45	28
50	30
55	30
65	25

Table 1. Time and speed data corresponding to ship maneuvers (Fig. 6)

Figure 6 displays the sequence of data recorded during maneuvers. The left plot indicates the raw data as recorded by the FOSS. The right plot shows the data after application of an Empirical Model Decomposition (EMD) to remove the trend. The time axis shown in Figure 6 is shown relative to the beginning of the maneuvers. Table (1) lists the speeds (in knots). Several observations can be made regarding the deckplate response to high speed turns. First and foremost, the maximum strains observed due to the ship maneuvers were roughly +/- 10 με. These values are extremely small and are not likely to be the cause of any significant structural damage. Although the magnitude of the strain values do increase with speed, the ship will not likely see maximum knots for prolonged periods thus we do not expect hard turns at speed to be an issue. A minor point of interest concerns the ambient noise associated with the engine vibration.

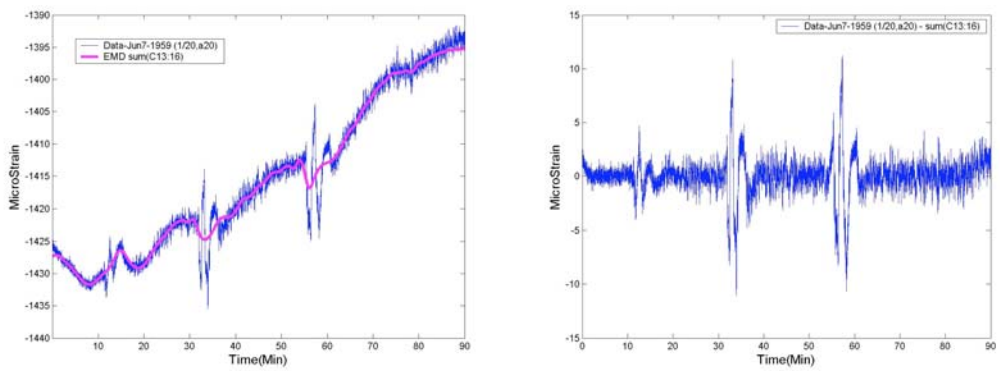

Figure 6. Raw sensor data recorded from sensor 3 of rosette C showing the strain values recorded during the series of turns (left). Data with trend removal using EMD signal processing technique (right).

Clearly as the speed of the ship is increased the ambient engine noise is also increased and is captured nicely by the sensors. This affect can also be observed in the time-frequency plot of Figure (7). The detrended signal is superimposed (in white) in order to highlight the influence of the maneuvers on frequency content. Clearly there is an increase in energy at roughly 2.5 Hz during the turns, but also a small, but observable, increase due to ambient engine noise as the speed is ramped up.

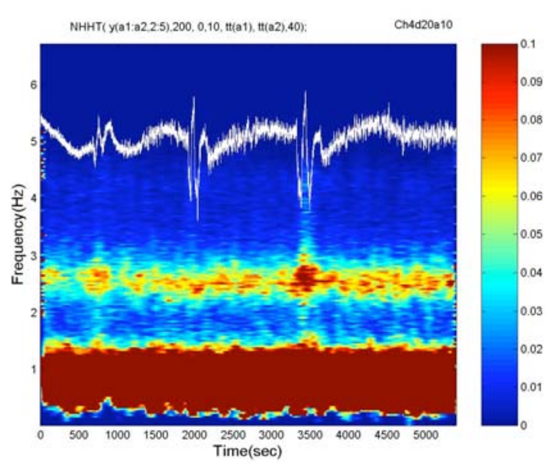

Figure 7. Time Frequency plot with raw data superimposed (in white). Most frequency content is below 1Hz. Energy content at 2.5 Hz tracks well with ship maneuvers.

As was previously mentioned, testing was also performed to see whether or not slewing of the AN/SPG-62 Illuminator mounted to the surface of the deckplate caused excessive strain. No such strain was observed throughout these tests. We could discern no difference from the ships ambient vibrations and therefore conclude AN/SPG-62 Illuminator motion is not an issue with regard to the deck cracking.

Section 4: Conclusions and Recommendations

The data collection from this particular ship was largely successful and resulted in some preliminary results that are of use in understanding the cause of the recurring deck cracking. First of all, the primary source of strain on the deckplate can not be attributed to ship maneuvers or slewing of the AN/SPG-62 Illuminator. Neither action resulted in more than 10$\mu\varepsilon$ of load. Secondly, the primary strain does not appear to be the result of thermal affects. Rather there appears to be a large compressive load that forms in the deckplate as the ship gets underway. At present time, on the basis of limited data, we can not draw strong *conclusions* about the source of this load. In order to definitively determine the cause of these strains we recommend a second deployment of the sensing system. The focus of this deployment would be on the long-term strains observed as the ship gets underway and returns to port. Such a deployment would allow us to focus on capturing this long term strain behavior and determining its source, as well as corroborating these preliminary results.

Section 5: Future Enabling Technology Vision

Integrating this technology, with proper engineering design, into hull forms at new construction and capturing *real-time hull load data could significantly expand Fleet operator's envelope for ship performance* by reporting actual forces acting on the hull at any given point in time. This could enable ships to operate in higher sea state at higher speeds; enable submarines to dive deeper and faster; enable Commanding Officer's power of informed decision, each of which is not enabled based on ship operational parameters being limited by modeling and safety factor alone.

Acknowledgements: This report not only demonstrates the viability of FOSS technology, but also the sponsors', authors', and end-users' interest in pursuing technologies that support and promote resolution to current Fleet problems. This task also validates envisioning future roles for similar technologies. The participants of this report extend their gratitude to Dr. Perez, et al. at ONR, the Staff at Commander, Naval Surface Force Atlantic (CNSF) and especially to the Command and crew of the ship for ardently supporting the organizational synergy created within this project to make it a success.

[i] J. P. Soisson and E. Murcko, "Trip report: Visit with USS VELLA GULF (CG 72) to inspect and discuss cracked superstructure deckplate", NAVSEA: Ser 61/06-489, Aug. 11, 2006.

[ii] J. P. Soisson and E. Murcko, "Trip report: Metallurgical evaluation of cracked intake bulkhead from USS VICKSBURG (CG 69) and corrective measures for 5xxx series aluminum alloy material", NAVSEA: Ser 61/61-500, Aug. 25, 2006.